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# XMM-Newton observations of the black hole X-ray transient XTE J1650–500 in quiescence

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**ABSTRACT**
We report the result of an *XMM-Newton* observation of the black-hole X-ray transient XTE J1650–500 in quiescence. The source was not detected and we set upper limits on the 0.5–10 keV luminosity of $0.9 - 1.0 \times 10^{31}$ erg s$^{-1}$ (for a newly derived distance of 2.6 kpc). These limits are in line with the quiescent luminosities of black-hole X-ray binaries with similar orbital periods (∼7–8 hr).

**Key words:** stars: individual (XTE J1650–500) — X-rays: stars

## 1 INTRODUCTION

XTE J1650–500 is an X-ray transient that was discovered with the *Rossi X-ray Timing Explorer (RXTE)* in 2001 (Remillard 2001), during the only outburst of the source detected thus far. Based on its spectral and variability behavior XTE J1650–500 can be classified as a black hole candidate X-ray binary (see e.g. Kalemci et al. 2003; Homan et al. 2003; Rossi et al. 2004). Optical observations of the source revealed an orbital period of 0.3205 days and a mass function $f(M) = 2.73 \pm 0.56\,M_\odot$ (Orosz et al. 2004). Combined with a lower limit of $50^\circ \pm 3^\circ$ on the inclination, this translates into an upper limit on the black hole mass of $7.3\,M_\odot$, with a most likely mass of ∼4 $M_\odot$ (Orosz et al. 2004). Observations with *XMM-Newton* during outburst revealed a red-shifted Fe K-alpha line (Miller et al. 2002), which suggests that the compact object is a rapidly spinning black hole. XTE J1650–500 has been observed at luminosities (0.5–10 keV) ranging from $\sim 4 \times 10^{33}$ erg s$^{-1}$ to $\sim 8 \times 10^{36}$ erg s$^{-1}$ (for an assumed distance of 2.6 kpc, see Appendix A). At low luminosities, when it was in the hard state, the source showed two properties that have not been shown by any other transient black hole X-ray binary. Oscillations with a period of 14 days were observed, which had similarities to the longterm oscillations observed in the transient millisecond-second X-ray pulsar SAX J1808.4-3658 (Wijnands 2004). Also, six X-ray flares were observed (Tomsick et al. 2003). Using *Chandra* and *RXTE* data, Tomsick et al. (2004) observed spectral softening towards low X-ray luminosities, with the spectral power-law index evolving from 1.66±0.05 at $9 \times 10^{34}$ erg s$^{-1}$ (1–9 keV) to 1.91±0.13 at $1.5 \times 10^{34}$ erg s$^{-1}$. Prior to our work, the source was not observed in quiescence.

In this paper we report the results of an *XMM-Newton* observation of XTE J1650–500, performed when the source was believed to be in quiescence, more than two and a half years after the source was last observed with *RXTE* and *Chandra* in 2002. About fourteen black-hole X-ray binaries (BHXBs) have so far been observed in quiescence (most of them with *Chandra* and *XMM-Newton*), with detected 0.5–10 keV luminosities ranging from $4 \times 10^{30}$ erg s$^{-1}$ to $1 \times 10^{33}$ erg s$^{-1}$ (Hameury et al. 2003, see Tomsick et al. (2003) for a complete list of observed sources). These studies of quiescent BHXBs are playing a central role in the debate on the existence of black-hole event horizons. As noted by various authors (Narayan et al. 1997a; Menou et al. 1999; Garcia et al. 2001), BHXBs have substantially lower quiescent X-ray luminosities than neutron star X-ray binaries (NSXBs) with similar orbital periods. Usually, the neutron-star systems have a relatively bright soft, thermal component which is lacking in the BHXBs (but sometimes also in NSXBs [Campana et al. (2002); Wijnands et al. (2005)]). This soft component is interpreted as coming from the neutron-star surface, either due to the cooling of the neutron star and/or due to a crustal heating by residual accretion onto the neutron star's surface. The absence of such a thermal component and the lower quiescent X-ray luminosities are therefore often interpreted as an indication for the presence of an event horizon in BHXBs. However, since the source of quiescent X-ray emission in both the BHXBs and the NSXBs is still under debate, this conclusion remains uncertain.

Several sources of quiescent X-ray emission have been proposed for BHXBs. It has been suggested (see e.g. Narayan et al. 1997a,b; Hameury et al. 2003, and references therein) that advection dominated accretion flows (ADAFs) can explain the optical/X-ray ratios and X-ray spectra seen in quiescence. These flows also

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provide a possible explanation for the luminosity difference between black-hole and neutron-star X-ray transients in quiescence. Bildsten & Rutledge (2000) suggested that coronal emission from rapidly rotating companion stars might be responsible for the quiescent X-ray luminosity. However, it was shown by Kong et al. (2002) that the X-ray spectra of five of the six quiescent BHXBs they studied were inconsistent with those of stellar coronae. Finally, assuming that the hard state of BHXBs extends all the way to quiescence, another possibility is X-ray emission from a jet (Markoff, Falcke, & Fender 2001; Markoff et al. 2003). Regardless of the exact mechanism for the X-ray emission, Fender et al. (2003) suggested that at very low mass accretion rates BHXBs should enter a 'jet-dominated' state in which most of the energy is released in a jet outflow instead of X-rays from the accretion flow. At similarly low mass accretion rates, the energy release from NSXBs is not expected to be dominated by jets.

In addition to the luminosity difference between quiescent BHXBs and NSXBs, there also appears to be a positive correlation between the quiescent luminosities and orbital periods of BHXBs (see e.g. Hameury et al. 2003). Based on a comparison with sources that have similar orbital periods one would expect a quiescent X-ray luminosity for XTE J1650–500 of $\sim 10^{30}$–$10^{31}$ erg s$^{-1}$.

## 2 ANALYSIS AND RESULTS

XTE J1650–500 was observed with *XMM-Newton* from March 6 2005 14:59 UT until 03:42 UT the following day (Obs-Id: 0206640101). For this paper we analyzed pipeline-production data from the EPIC-pn and two EPIC-MOS instruments, using SAS version 6.1.0. All three instruments were used with a medium thickness filter. For each of the three instruments background light curves were produced from all CCDs combined, selecting only photons above 10 keV (with PATTERN=0 and FLAG=0). The resulting light curves showed very strong flaring for ∼65% (MOS) and ∼75% (pn) of the observation. Intervals free of flaring were singled out by selecting 50 s time bins with count rates below 0.65 count s$^{-1}$ (pn) or below 0.2 counts s$^{-1}$ (MOS). The resulting good time intervals were applied to the CCD on which the source was located, using the standard selection criteria (PATTERN$\leqslant$4 for EPIC-pn, PATTERN$\leqslant$12 for MOS, and FLAG=0). This resulted in effective exposure times of 12 ks (pn) and 18 ks (MOS).

Images were produced in the 0.5–10 keV band with a binning that resulted in pixels of 5$''$, close to the full-width-at-half-maximum of the point spread function (PSF) of the EPIC cameras. None of the images showed an apparent excess of photons at the location of the source. Images in narrower energy bands across the 0.5–10 keV range did not show an obvious source detection either.

Next, we ran the SAS task `edetect_chain` (with default input parameters) simultaneously on the three 0.5–10 keV images. No source was detected at the position of XTE J1650–500 (R.A.=16:50:01.0, Dec=-49:57:45). For the faintest source[1] detected with `edetect_chain` we calculated the flux using PIMMS, assuming[2] an $N_H$ of $5.3\times10^{21}$ atoms cm$^{-2}$ and a power-law spectrum with indices (Γ) varying between 1.5 and 2.5. For EPIC-MOS we found unabsorbed fluxes between 2.0(7)$\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ ($\Gamma = 2.5$) and 2.2(8)$\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ ($\Gamma = 1.5$) and for EPIC-pn we found fluxes between 3.1(9)$\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ ($\Gamma = 2.5$) and 3.5(9)$\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ ($\Gamma = 1.5$). These numbers serve as conservative upper limits on the flux of XTE J1650–500.

Alternative upper limits were obtained from the 0.5–10 keV images by extracting the counts from a 20$''$radius circle centered on the position of XTE J1650–500. This was done using the tool `funcnts` from the FUNTOOLS package, which also extracted counts from a large pre-defined source-free background region and corrected for differences in the exposure map values between the source and background region. The numbers of counts (source + background) within this region were 22, 18 and 35, for MOS1, MOS2, and pn, respectively. Using the tables in Gehrels (1986) this leads to single-sided 3$\sigma$ upper limits of 40.1, 34.8, and 56.7 on the total counts. The expected background counts for the three source regions were, 26.9, 21.5 and, 44.1, respectively, with errors of less than 5%. Correcting for background and using the average exposure map values (17.7 ks, 15.6 ks, and 10.3 ks), this gives upper limits on the source count rate of $7.5\times10^{-4}$, $8.5\times10^{-4}$ and $1.23\times10^{-3}$ counts s$^{-1}$. Using PIMMS, correcting for encircled energy (from PSF integration[3]), and assuming an $N_H$ of $5.3\times10^{21}$ atoms cm$^{-2}$, we get the following (unabsorbed) flux upper limits for power-law spectra: $1.8-2.0\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (MOS1), $2.1-2.3\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (MOS2), and $1.1-1.3\times10^{-14}$ erg cm$^{-2}$ s$^{-1}$ (pn), with the high values corresponding to $\Gamma = 1.5$ and the low values to $\Gamma = 2.5$.

## 3 CONCLUSIONS

We have observed the black hole X-ray transient XTE J1650–500 in quiescence. The source was not detected. Assuming a distance of 2.6 kpc (see Appendix A), the most stringent upper limits on 0.5–10 keV luminosity are $0.9-1.0\times10^{31}$ erg s$^{-1}$ (depending on the assumed shape of the spectrum), which corresponds to $\sim 1.8\times10^{-8}$ times the Eddington luminosity ( $L_{Edd}$) for a black-hole mass of $4M_\odot$ (Orosz et al. 2004). These values are similar to the quiescent luminosities of other BHXBs with similar orbital periods, even for a distance as low as 2 kpc (which is consistent with our estimate). Our luminosity upper limits follow the observed relation between orbital period and quiescent luminosity, although, as mentioned also by others, more systems with long periods need to be observed to firmly establish the existence of such a relation.

Longer observations are needed to detect XTE J1650–500 in quiescence or provide more stringent and useful upper limits on its luminosity, preferably with *Chandra*, which suffers relatively less from background flaring than *XMM-Newton* and has a much lower non-flaring background than *XMM-Newton*.

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[1] XMMU J165002.6-495333, a total of 49±11 source counts were detected from this source (pn and MOS combined)

[2] The value of $N_H$ was obtained from spectral fits to *XMM-Newton* data of XTE J1650–500 in outburst (Miller et al. 2002) and is consistent with values obtained from radio measurements (Dickey & Lockman 1990).

[3] We extracted from a 20$''$radius, while PIMMS expects count rates from a 15$''$region. Using figures from the XMM Users' Handbook, we estimate the correction factors to be 0.92 (mos) and 0.91 (PN).

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## APPENDIX A: DISTANCE ESTIMATE

Here we derive a distance estimate for XTE J1650–500, based on the luminosity at which the source made the transition from the spectrally soft state back to the spectrally hard state at the end of its 2001 outburst. Maccarone (2003) studied such transitions in six black hole X-ray transients and found that they occur in a narrow rang of luminosity: 1–4% of the Eddington luminosity ($L_{Edd}$), with an average of 2% of $L_{Edd}$. The definition of the 'transition to the hard state' is not entirely clear from Maccarone (2003), but we pick an *RXTE* observation of XTE J1650–500 in which the spectral power-law index was around 2, similar to the *RXTE* observation that Maccarone (2003) used for XTE J1550–564. Note that Maccarone (2003) assumed a spectral index of 1.8 and an exponential cutoff at 200 keV for the bolometric correction (to the 0.5 keV to 10 MeV range). No observation with such a spectral index was present in the coverage of the soft-to-hard state transition in XTE J1650–500, with a spectral index of 2 being the closest. We analyzed *RXTE* observation 60113-01-39-02 and fitted the 3–100 keV spectrum with a simple phenomenological model consisting of a disk blackbody, a cut-off power law, and a smeared edge, with $N_H$ fixed to $5.3 \times 10^{21}$ atoms $\mathrm{cm}^{-2}$. The unabsorbed flux, extrapolated to the 0.5 keV to 10 MeV range, is $1.4 \times 10^{-8}$ erg $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Assuming that this flux corresponds to 2% of $L_{Edd}$, which is $\sim 1.1 \times 10^{37}$ erg $\mathrm{s}^{-1}$ for a 4 $M_{\odot}$ black hole, we derive a distance of 2.6±0.7 kpc. This is consistent with the distance of 3 kpc derived by Corbel et al. (2004), following a similar method. The main contributors to errors on the distance are the spread in the fraction of $L_{Edd}$ at which the soft-to-hard transition occurs (fractional error ∼50%) and uncertainties introduced by extrapolating well outside the spectral fit range (∼30%).

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